Large-Eddy Simulations of Tropical Convective Systems, the Boundary Layer, and Upper Ocean Coupling

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LONG-TERM GOAL

Improve operational numerical weather prediction (NWP) models to more accurately simulate the interaction of tropical deep convection and atmospheric and oceanic boundary layers.

OBJECTIVES

Investigate tropical convection and upper ocean circulations on scales from 100 m to 200 km. Elucidate specifically how the ocean mixed layer responds to forcing from atmospheric convection such as wind and precipitation, and thus how surface fluxes depend on the history of convective events. Perform high-resolution coupled atmosphere-ocean numerical model simulations, whose fidelity is a benchmark for operational models and parameterizations. Insights gained from these simulations will be used to improve parameterizations used in operational scale models, and to refine hypotheses in collaboration with investigators working on observational field studies in the Indian and West Pacific Oceans.

APPROACH

Intraseasonal variability in the tropics is dominated by the Madden-Julian Oscillation (MJO), which generates large-scale variability in the structure and organization of deep convective cloud systems. MJO events consist of multiple scales of convective activity, from single kilometer-sized cells to circulations encompassing half of the tropical Pacific. Key factors for tropical convection include sea-surface evaporation and large-scale atmospheric moisture convergence, which both depend on sea-surface temperature and wind speed. Most numerical models do not resolve turbulent and convective scales, nor do they simulate the MJO accurately. We plan to investigate how convection during the active phase of MJO affects and interacts with the ocean mixed layer. We will perform large eddy simulation (LES) of organized convective systems, which resolve boundary layer eddy scales to

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mesoscale convective towers. These numerical simulations will reveal how atmospheric convection alters air-sea fluxes and the ocean boundary layer, and will refine hypotheses on coupling between the ocean and atmospheric boundary layer during MJO events, to be tested during the field campaign. Processes on these scales are gaining importance in operational NWP models as the realism of convection increases along with model resolution.

WORK COMPLETED

Research during the second year of this project has focused on conducting large-eddy simulation (LES) experiments of tropical convection over a range of atmospheric conditions. As part of this effort, a simplified bulk ocean model has been implemented by assuming a 3-m thick ocean mixed layer and allowing for variable bulk ocean temperature. This preliminary ocean model will be expanded to a column model using the K-profile parameterization for vertical mixing and wind driven ocean currents for lateral transport.

RESULTS

One of our main goals this year has centered on understanding how convection affects fluxes between the atmosphere and ocean, and how the ocean responds to convection. Individual convective cells and clusters with scales ranging from 10s to 100s of kilometers generate wind and rainfall variations that, along with radiative effects, influence the upper ocean heat budget. Ocean measurements like those taken during TOGA-COARE provide a single point perspective on how the upper ocean responds to atmospheric forcing.

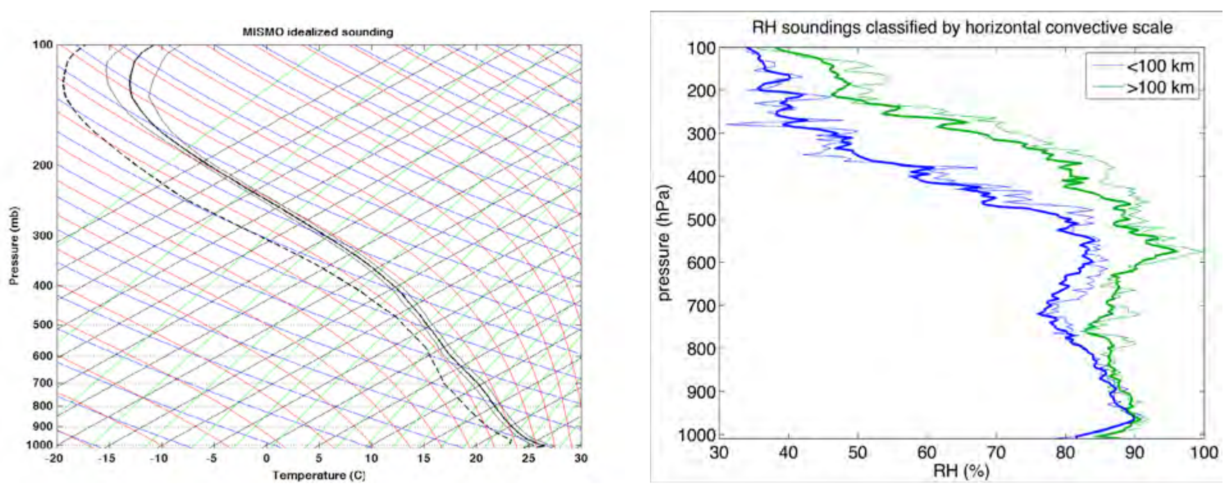

Figure 1. (a) Idealized sounding temperature (black solid) and dew point temperature (dashed) on a log-p skew-T diagram. (b) Relative humidity differences for horizontal convective scales less than 100 km (blue) and greater than 100 km (green). Thick lines are composite means, thin lines are composite medians.

Here we present results from the cloud resolving LES representing atmospheric convection for typical tropical Indian Ocean conditions using initial conditions collected during the MISMO experiment (Figure 1). This simulation has a crude ocean coupling where the ocean is represented through

$$\frac{\partial}{\partial t}\left(hT_{ml}\right) = \left(w'T'\right)_{bot} + F_{sh} + F_{lh} + R_{lw} + R_{sw}; \qquad \frac{\partial}{\partial t}\left(hS_{ml}\right) = \left(w'S'\right)_{bot} + \frac{F_{lh}}{\rho L_v} S_{ml} + PS_{ml}$$

with a fixed mixed layer depth *h* of 3 m and constant salinity. Results from the model are summarized in figure 2, representing cloud cover, surface fluxes, rainfall amount, and SST after 4 days.

Convection for this case is fully developed and near steady-state in terms of the cell size and number of convective regions. Cloud cover for the most part is limited in scope with about 20 percent of the area covered by convection. At the surface, the combined effects of convective cells has generated linear regions of enhanced winds and corresponding surface flux (fig. 1b), with values over 100 W m^{-2} associated with both active convective cells and where outflow boundaries have left behind significant wind divergence, for example near x = 50 km, y = 80 km. Fluxes also show the formation of internal gravity wave structures with wavelengths of about 10 km that are aligned perpendicular to the imposed wind shear and at times appear to enhance new convective cells.

Even with the absence of rainfall effects, convection has a significant influence on the SST with organized streaks of about 0.8 ^{o}C aligned with the average surface wind direction. These streaks are produced by surface turbulent heat flux variations forced by convection and systematic patterns in the surface radiative budget produced by clouds. The main point of this example is that ***even with a crude, bulk ocean structure and no precipitation effects, significant spatial variability is produced in the SST that could affect the organization and evolution of atmospheric convection.*** In our future work we will extend our understanding using a full-physics representation of the upper ocean with the K-profile parameterization.

As part of our study of convective coupling with the upper ocean, we are also interested in understanding processes that link convection with diurnal heating and determining if the ocean plays a significant role in the daily cycle. As shown by plots of the average rainwater mixing ratio and solar radiation, the model is able to adequately simulate a diurnal cycle of convection with rain fall typically a maximum just before sunrise. Simulations with a constant SST also generate this pattern suggesting that the diurnal cycle is primarily driven by atmospheric radiative processes. However, this bulk-ocean simulation does not account for thin, ocean warm layers that could develop because of salinity gradients. Future experiments will examine the impact of upper-ocean layering by employing a column ocean model in place of the current bulk configuration.

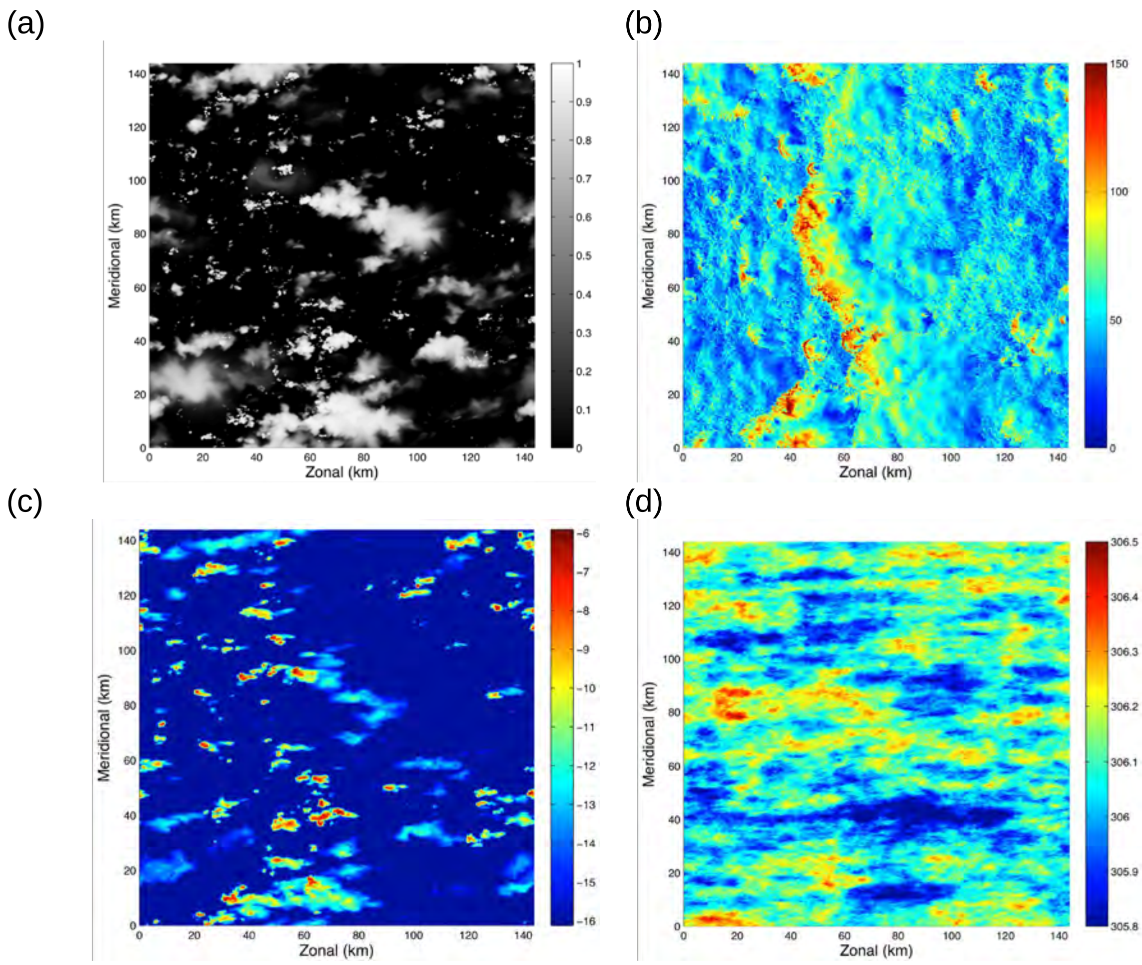

Figure 2. Cloud resolving LES results for (a) cloud albedo, (b) surface latent heat flux (W m^{-2}), (c) log rain water mixing ratio (kg/kg), and (d) sea surface temperature (K) after 4 days of integration. The model was initialized using average sounding data over November and December 2006 from the R/V Mirai during the Mirai Indian Ocean cruise for the study of the MJO-Convection Onset (MISMO).

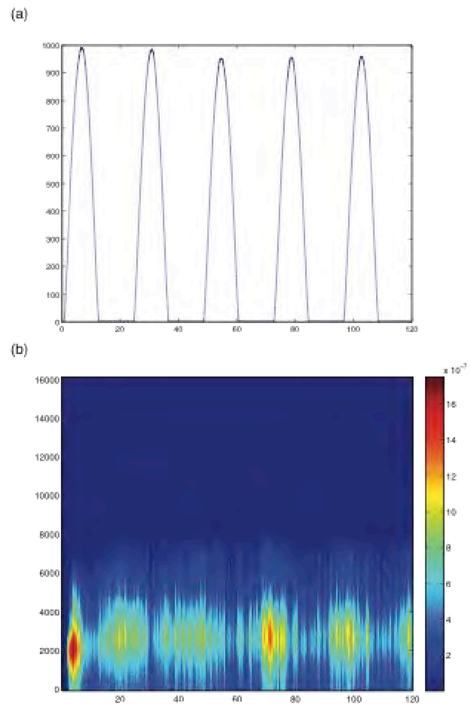

Figure 3. Average (a) surface solar radiation (W m^{-2}) and (b) rain water mixing ratio (kg/kg) as a function of model time.

RELATED PROJECTS

This project is part of the Indian Ocean Air-Sea DRI and is a part of DYNAMO. A related DYNAMO National Science Foundation project entitled "DYNAmics of the Madden-Julian Oscillation / Analysis of subsurface fluxes with coupled large-eddy simulation models" was recently funded and will provide a significant ocean component not proposed in the current project.